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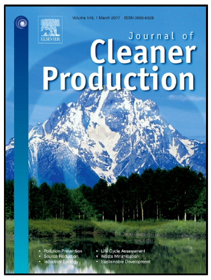

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Liquid Air utilization in air conditioning and power generating in a commercial building

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Abstract

Current air conditioning (AC) systems use a vapour compression system that consume a great amount of energy particularly during the peak times where most electricity suppliers facing difficulties to meet the users demands. Shifting the peak cooling demands to off-peak times using cold energy storage systems is a promising technique leads to save energy and to reduce the CO_2 emissions. This study presents new technology that uses the cold energy storage in form of liquid Air (LAir) or liquid nitrogen (LN2) to provide air conditioning and power to commercial buildings. Four different cryogenic cycles were modelled and analysis from a thermodynamic point view, and compared in terms of their, output power, cooling capacity, recovery efficiency, COP and how much energy could save when compared with the traditional AC system. The results showed that system performance when LAir is used is 21-25% higher than that of when LN2 is used, and the 4th configuration is the most effective cycle and it recovered up to 94% of the energy stored in LAir and 78% of the energy stored LN2. Compared to the conventional system at the current LAir and LN2 prices, the 1st, 2nd, 3rd and 4th cycles showed saving up to 15%, 24%, 31% and 37.5%, respectively, when LAir is used and -3.5%, 5%, 16% and 24%, consecutively, when LN2 is used.

Key words; liquid air/nitrogen; cryogenic system; air conditioning; peak demand; cold storage

1- Introduction

Conventional air conditioning (AC) systems use a vapour compression system that consumes a great amount of energy particularly during the peak times, and the demands of these systems have increased rapidly over the last few decades. Forecasts have shown that space cooling demands in Europe will increase rapidly over the next 15 years by 72% and will reach 30 times its current value by 2100 (Ahmad et al., 2016; Cox, 2012; Davis and Gertler 2015). Shifting the peak cooling demands to off-peak times using cold energy storage systems is a promising technique leads to save energy, to reduce the CO_2 emissions and to reduce the system size (Navidbakhsh et at., 2013). However, the performance of this technique affects significantly by the chosen storage medium, storage temperature and the operating strategy (Zhai et at., 2013).

There is a new cooling systems use cold storage medium in form of liquefied gases such as liquefied natural gas, air, nitrogen and CO_2 was also reported, and liquid air / nitrogen were considered as the most attractive storage medium due their high energy density, availability and environmental friendly (Knowlen et at., 1998). Place, 1909 developed LAir cooling system to cool railway carriages to preserve food by evaporating it in channels fitted around the cooling space. An air conditioning uses liquid air was developed by Harold in 1960 where the liquid air is evaporated in a heat exchanger then vented to the cooling space. A liquefied nitrogen and natural gas uses to cool a food transport lorry where the liquefied gases evaporated and superheated in heat exchanger fitted in the cooling space roof to generate cooling and then the mixture uses to run the lorry engine (Newman et al., 2014). Saia et al., 1994 modified the conventional refrigerator of a food transport lorry which uses to transfer a frozen food, using a liquefied carbon dioxide. The system evaporates liquid CO_2 in a heat exchanger fitted around the cooling space and provides cool at a wide range of sub-zero temperatures. Cooling the cutting tools using LN2 with a compressed air and lubricating fluids was also reported and tested by many researchers. This technique leads to reduce the tip temperature, cutting force, the consumption of the cutting fluid and increase the cutting speed and the feed rate (Tazehkandi et al., 2015; Giasin et at., 2016; Pereira et al., 2016). An air conditioning system and refrigerator that use a direct spray of LAir into the cooling space were reported by (Garlov et at., 2002). Skobel et al. 2012 developed a beverage dispenser that uses liquid nitrogen (LN2) cooling system and it was effective in producing cooling, quite, suitable for remote areas and environmental friendly. A LAir engine that provides cooling and power for food transport vehicles was presented by (Strahan et al., 2013; Dearman, 2015) and the engine is used to run a traditional AC system and other auxiliary devices. Exhaust cool from the engine is used to enhance the performance of the AC system by reducing its condenser temperature. A comprehensive study of various cryogenic cycles that use LN2 to provide cooling and power for domestic applications was carried out by Ahmad et al. 2016, and the results showed that, at the current LN2 prices savings up 36% was achieved and 74% of the LN2 stored energy was recovered (Ahmad et at. 2016)

The above mentioned work shows using cold storage systems in form of liquid Air/nitrogen to provide cooling and power is feasible and leads to save energy, reduce the CO_2 emissions and reduce the peak electricity demands. The last mentioned work was used LN2 to provide cooling and power for domestic applications, however, mere than 25% of the energy consumed to produce LN2 does not recovered. The current study aims to investigate using LAir, which consumes 20% less energy than LN2, to provide cooling and power to a commercial building located in Ahwaz, Iran (Navidbakhsh, et al., 2013). A thermodynamic analysis of four different cryogenic cooling and power cycles were carried out modeled using MATLAB integrated with REFPROP software. These cycles were compared in terms of their cooling capacities and output powers, recovery efficiencies and COPs, and also were compared with the conventional AC system (MATLAB, 2008; REFPROP, 2010).

2- Proposed cryogenic cooling and power cycles

The proposed systems use the cold stored energy in form of liquid air to generate air conditioning and power for commercial buildings at the peak times to save energy, to increase the national electricity grid stabilities by reducing the peak electricity demands. The proposed systems consist of two circuits; the first one circulates a secondary coolant to meet the building cooling demands. This cooling load is used as heat source to the second circuit (LAir cycle) which provides cooling and power by evaporating pressurized LAir and expanded it in an expander. Four different cryogenic cycles were modelled using MATLAB combined with REFPROP software to find out the most efficient cycle that recovers most of the energy stored in LAir. The model investigates wide range of LAir inlet pressure (represented by P_{2A} in the following figures) to find out how it will affect the system performance, and a cost analysis to compare the conventional AC system with the proposed systems was also carried out.

The first cycle is shown in Fig. 1(a, b) where the liquefied air is pumped to a coil immersed inside the cooling tank to be evaporated and superheated by the secondary coolant load before it passes through an expander to generate power. The expansion process can be either adiabatic or isothermal expansions as shown in Fig. 3b. In the adiabatic expansion scenario, the expansion process reduces the air outlet temperature so it returns to the cooling tank in order to increase the system cooling capacity. However, for the isothermal expansion scenario (that represented by dash line in Fig. 1b) where the expanded air leaves at the secondary coolant temperature, so it vents directly to the atmosphere. This later scenario has advantages by absorbing more heat in the expansion process which increases the system cooling capacity and output power. Also the inlet pressure (P_{2A}) can be increased to more than 500 bar whereas this value cannot exceeds 100 bar in the first scenario duo to lowering the exit temperature below saturated line as shown in the expansion process (a-b) in Fig.1b. More than 80% of the isothermal expansion can be practically achieved by gaining heat from the surroundings using secondary fluid or by having a high value of surface to volume ratio expander or by three stage expander with reheat after the first and the second stage (Ahmad et al., 2016; North, 2008; Knowlen, et al., 1997; Vitt and Peter, 1997; Ordonez, 2000).

The second cycle is presented in Fig. 2(a, b) where the previous LAir cooling and power cycle is used to drive a closed Brayton cycle by cooling down its working fluid (in the process 4B-1B) while the LAir evaporates and superheats in the process (2A-3A). The cooling process followed by compression (1B-2B), heating (2B-3B) and expansion (3B-4B) processes as shown in the Fig.2. The closed Brayton cycle output power affects by its mass flow rate, which depends on the selected evaporator outlet temperature (T_{3A}), and its pressure ratio, which restricts by the compressor outlet temperature (T_{2B}) which has to be less than the secondary coolant temperature. These values and the closed cycle working fluid should be carefully selected to achieve the maximum output power and to avoid any condensation in the evaporator. The closed Brayton working fluid should has boiling point lower than that of LAir and many gases can be used such as Neon, Helium or Hydrogen, and the later one was selected for the current work.

The third cycle is similar to the second cycle; however, in this case LAir power cycle drives a closed Rankine cycle which more efficient the Brayton cycle. The cycle is shown in Fig.3(a, b) where closed Rankine cycle (1R, 2R, 3R and 4R) uses LAir to condense it working fluid in HE1 while it evaporates and superheats. The condensed fluid is pumped to a separate heat exchanger immersed in the cooling tank (1R-2R) to evaporate and superheat in the process (2R-3R) then expanded in a separate expander (3R-4R). The closed cycle working fluid should be carefully selected to achieve the maximum output power. Xenon with boiling temperature of -108 °C at atmospheric pressure was selected as working fluid of the closed Rankine cycle in this study.

Fig.4(a, b) shows the fourth cycle where the LAir cycle drives two cascades closed Rankine cycles which are named as the first and the second closed Rankine cycles. The first closed Rankine cycle represents by (1R, 2R, 3R, 4R and 5R) and the second closed Rankine cycle represents by (1R', 2R', 3R' and 4R'). The LAir evaporates and superheats (2A-3A) in HE1 while it condenses the first closed Rankine cycle working fluid (5R-1R). Then the superheated air passes through HE2 and the cooling tank (3A-4A and 4A-5A) for further heating before it expands in an expander (5A-6A). The condensed fluid of the first closed cycle is pumped to HE2 (1R-2R) where it evaporates (2R-3R) and condenses the second closed cycle working fluid (4R'-1R'). Then the vapour passes through a separate expander (4R-5R) after been superheated in the cooling tank (3R-4R). The second closed cycle working fluid pumps to the cooling tank (1R'-2R') where it evaporates and superheats (2R'-3R') then passes through another separate expander. The working fluids of the two closed Rankine cycles should be carefully selected to meet the cycle and the application requirements. For the current study R14, which boils at -127 °C at the atmospheric pressure, was chosen as working fluid for the first closed cycle and R13, which boils at -81 °C at the atmospheric pressure, was chosen as working fluid for the second closed cycle.

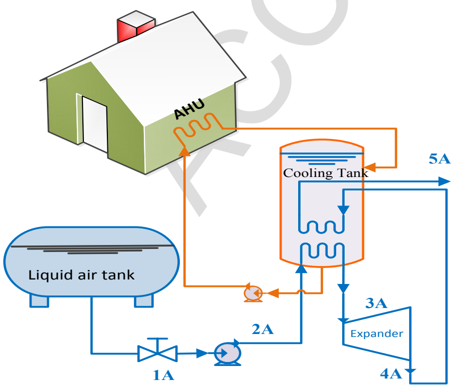


Fig.1a First cycle, LAir cooling and power cycle

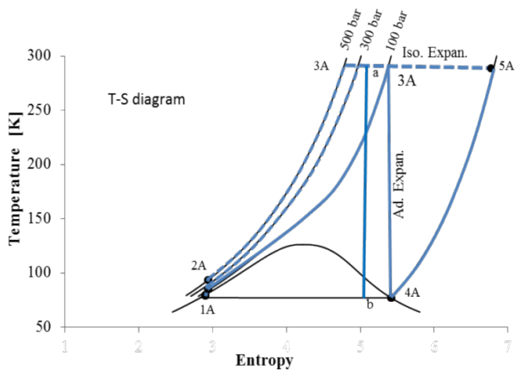


Fig.1b First cycle's T-S diagram.

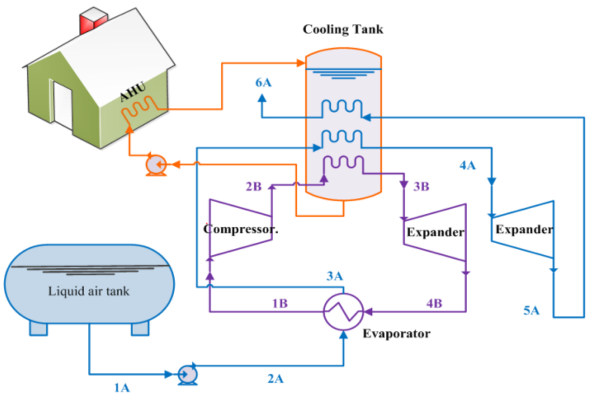


Fig.2a Second cycle, LAir drives closed Brayton cycle

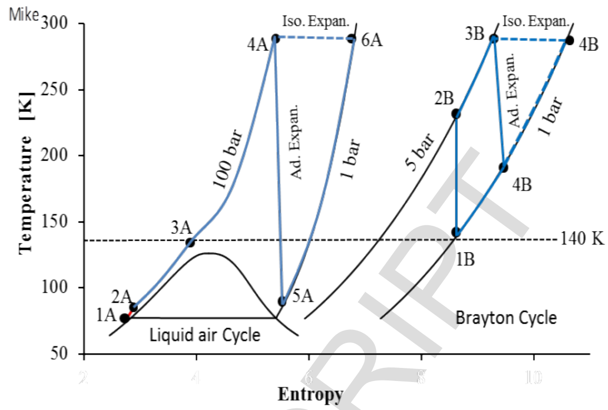


Fig.2b Second cycle 's T-S diagram.

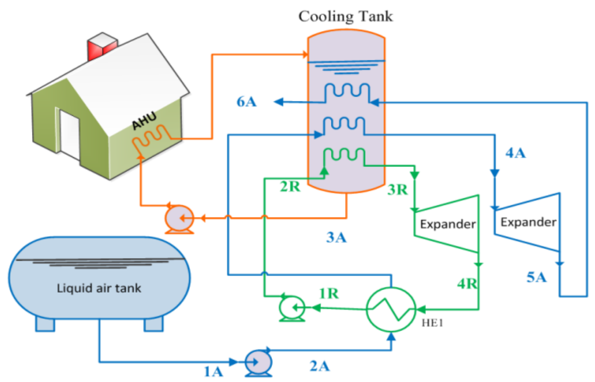


Fig.3a Third cycle, LAir drives closed Rankine cycle

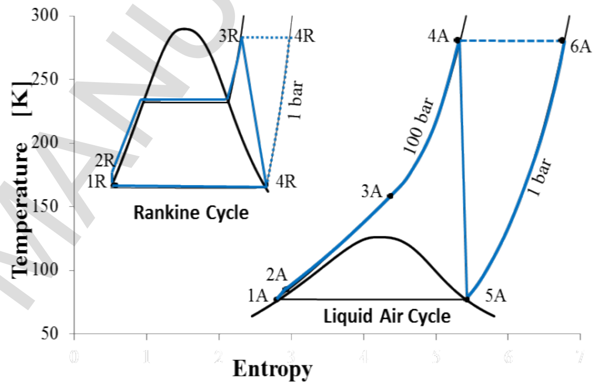


Fig.3b Third cycle's T-S diagram

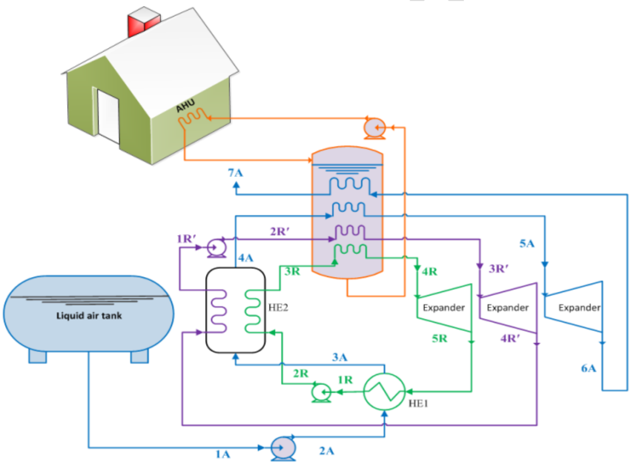


Fig.4a Fourth cycle, LAir drives two closed Rankine cycles

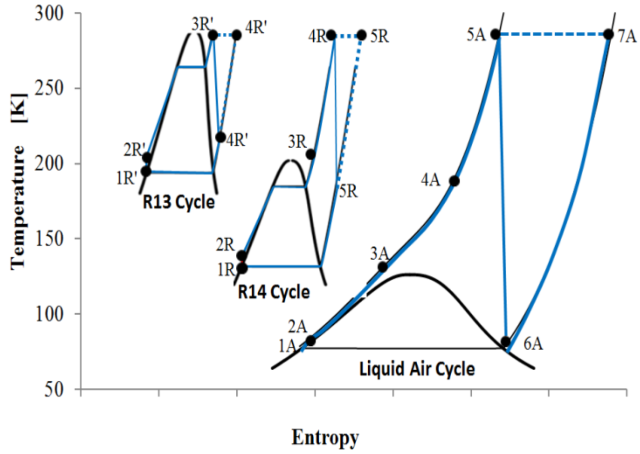


Fig.4b Fourth cycle's T-S diagram.

3- Thermodynamic modelling

The proposed cycles were analysed from thermodynamic point view to find out the most effective system which recovers most the energy storage in LAie/LN2, and provide higher output power and cooling capacity to for the selected application. A mathematical model was developed for each of the above cycles using MATLAB combined with REFPROP software to (a) calculate the properties of all working fluids at each state in the cycle, (b) optimizer the operating conditions, (c) solve the energy and mass balance equations, (d) calculate LAir/LN2 mass flow rate, power output, cooling capacity, efficiency and the cycle COP. Both expansion processes were considered in the current study and a wide range of the inlet pressure (P_{2A}) was discovered. The model was simplified by the following:

- Liquid enters to the system at 78 K at near atmospheric pressure, and leaves as gas at 283 K.
- Heat absorbs or loss from/into the surroundings is negligible.
- The inlet pressure of all pumps and compressors is atmospheric pressure.
- The isentropic efficiency of pumps, expanders and compressors are 90%, 90% and 85% respectively.
- The pressure drop in all cycle's components is negligible.

For the first cycle shown in Fig.1 (a, b), the specific work output was calculated using Eqs.1 when adiabatic expansion process is considered and Eq.2 when isothermal expansion process is considered.

$$W_{Ad} = [(h_{3A} - h_{4A}) - (h_{2A} - h_{1A})] \quad (1)$$

$$W_{Iso} = [T_{tank}(s_{4A} - s_{3A}) - (h_{2A} - h_{1A})] \quad (2)$$

Where; W is specific work in kJ/kg, h is the specific enthalpy in kJ/kg T is temperature in K and s is specific entropy in kJ/kg-K. Whereas the subscripts *Ad, Iso, A* and *tank* refer to adiabatic expansion, isothermal expansion, LAir cycle and cooling tank, respectively. While the specific cooling capacity was calculated using Eqs.3 for the adiabatic expansion and Eqs.4 for the isothermal expansion process.

$$CC_{Ad} = [(h_{3A} - h_{4A}) + (h_{5A} - h_{4A})] \quad (3)$$

$$CC_{Iso} = [T_{tank}(s_{4A} - s_{3A})] \quad (4)$$

Where; CC is specific cooling capacity in kJ/kg.

Regarding the second cycle shown in Fig.2 the ratio of the closed Brayton cycle mass flow rate to the LAir mass flow rate was calculated first by applying energy balance equation to the fluids enter and leave the evaporator using Eq.5.

$$m_r = \frac{\dot{m}_B}{\dot{m}_A} = \frac{(h_{3A} - h_{2A})}{(h_{1B} - h_{4B})} \quad (5)$$

Where; $\dot{m}_B$ is the mass flow rate in kg/s for the closed Brayton cycle, and $\dot{m}_A$ is the mass flow rate of the LAir cycle in kg/s. The specific output works were calculated using Eqs. 6-8 for the adiabatic expansion and Eqs. 9-11 for the isothermal expansion processes.

$$(W_A)_{Ad} = [(h_{4A} - h_{5A}) - (h_{2A} - h_{1A})] \quad (6)$$

$$(W_B)_{Ad} = m_r[(h_{3B} - h_{4B}) - (h_{2B} - h_{1B})] \quad (7)$$

$$W_{Ad} = (W_A)_{Ad} + (W_B)_{Ad} \quad (8)$$

$$(W_A)_{Iso} = [T_{tank}(s_{5A} - s_{4A}) - (h_{2A} - h_{1A})] \quad (9)$$

$$(W_B)_{Iso} = m_r[T_{tank}(s_{4B} - s_{3B}) - (h_{2B} - h_{1B})] \quad (10)$$

$$W_{Iso} = (W_A)_{Iso} + (W_B)_{Iso} \quad (11)$$

Where; the subscript A refers to the LAir cycle, and the subscript B refers to the closed Brayton cycle. The specific cooling capacity was calculated using Eq.12 when adiabatic expansion process is considered and Eq.13 when the isothermal expansion process is considered.

$$CC_{Ad} = [(h_{4A} - h_{3A}) + (h_{6A} - h_{5A})] + m_r(h_{3B} - h_{2B}) \quad (12)$$

$$CC_{Iso} = [T_{tank}(s_{5A} - s_{4A})] + m_r[T_{tank}(s_{4B} - s_{3B})] \quad (13)$$

In the same previous manner, the ratio of the closed Rankine cycle mass flow rate to the LAir mass flow rate for the third cycle shown in Fig.3 was calculated first by applying energy balance equation to the fluids enter and leave HE1 as in the following Eq14.

$$m_r = \frac{\dot{m}_R}{\dot{m}_A} = \frac{(h_{3A} - h_{2A})}{(h_{1R} - h_{4R})} \quad (14)$$

Where; $\dot{m}_R$ is the mass flow rate of the closed Rankine in kg/s and subscript R referred to the closed Rankine cycle, the specific output works were calculated using Eqs. 15-17 for the adiabatic expansion and Eqs. 18-20 for the isothermal expansion processes.

$$(W_A)_{Ad} = [(h_{4A} - h_{5A}) - (h_{2A} - h_{1A})] \quad (15)$$

$$(W_R)_{Ad} = m_r[(h_{3R} - h_{4R}) - (h_{2R} - h_{1R})] \quad (16)$$

$$W_{Ad} = (W_A)_{Ad} + (W_R)_{Ad} \quad (17)$$

$$(W_A)_{Iso} = [T_{tank}(s_{5A} - s_{4A}) - (h_{2A} - h_{1A})] \quad (18)$$

$$(W_R)_{Iso} = m_r[T_{tank}(s_{4R} - s_{3R}) - (h_{2R} - h_{1R})] \quad (19)$$

$$W_{Iso} = (W_A)_{Iso} + (W_R)_{Iso} \quad (20)$$

The specific cooling capacity was calculated using Eq.21 when the adiabatic expansion process is considered and Eq.22 when the isothermal expansion process is considered.

$$CC_{Ad} = [(h_{4A} - h_{3A}) + (h_{6A} - h_{5A})] + m_r[(h_{3R} - h_{2R}) \quad (21)$$

$$CC_{Iso} = [T_{tank}(s_{5A} - s_{4A})] + m_r[T_{tank}(s_{4R} - s_{3R})] \quad (22)$$

Regarding the fourth cycle shown in Fig.4 where the LAir cycle derives two cascades Rankine cycles, the ratio of mass flow rate of the first closed Rankine cycle working fluid to the LAir mass flow rate (m_{r1}) was calculated using the energy balance in HE1 as in Eq.23, and ratio of mass flow rate of the second closed Rankine cycles working fluid to the LAir mass flow rate (m_{r2}) was calculated using the energy balance in HE2 as in Eq.24

$$m_{r1} = \frac{\dot{m}_R}{\dot{m}_A} = \frac{(h_{3A} - h_{2A})}{(h_{5R} - h_{1R})} \quad (23)$$

$$m_{r2} = \frac{\dot{m}_{R'}}{\dot{m}_A} = \frac{m_{r1}(h_{3R} - h_{2R}) + (h_{4A} - h_{A3})}{(h_{4R'} - h_{1R'})} \quad (24)$$

Where; $\dot{m}_R$ is the mass flow rate in kg/s for the first closed Rankine cycle and $\dot{m}_{R'}$ is the mass flow rate in kg/s for the second closed Rankine cycle. The subscripts *R* is referring to the first second closed Rankine cycle, while the subscript *R'* is referring to the second closed Rankine cycle.

The specific work output was calculated using Eqs.(25-28) when the adiabatic expansion process is considered and Eqs. (29-32) when the isothermal expansion process is considered.

$$(W_A)_{Ad} = [(h_{5A} - h_{6A}) - (h_{2A} - h_{1A})] \quad (25)$$

$$(W_R)_{Ad} = m_{r1}[(h_{4R} - h_{5R}) - (h_{2R} - h_{1R})] \quad (26)$$

$$(W_{R'})_{Ad} = m_{r2}[(h_{3R'} - h_{4R'}) - (h_{2R'} - h_{1R'})] \quad (27)$$

$$W_{Ad} = (W_A)_{Ad} + (W_R)_{Ad} + (W_{R'})_{Ad} \quad (28)$$

$$(W_A)_{Iso} = T_{tank}(s_{6A} - s_{5A}) - (h_{2A} - h_{1A}) \quad (29)$$

$$(W_R)_{Iso} = m_{r1}[T_{tank}(s_{5R} - s_{4R}) - (h_{2R} - h_{1R})] \quad (30)$$

$$(W_{R'})_{Iso} = m_{r2}[T_{tank}(s_{4R'} - s_{3R'}) - (h_{2R'} - h_{1R'})] \quad (31)$$

$$W_{Iso} = (W_A)_{Iso} + (W_R)_{Iso} + (W_{R'})_{Iso}$$

(32)

The specific cooling capacity was calculated using Eq.33 when the adiabatic expansion process is considered and Eq.34 when the isothermal expansion process is considered.

$$CC_{Ad} = [(h_{5A} - h_{4A}) + (h_{7A} - h_{6A})] + m_{r1}[(h_{3R} - h_{2R}) + m_{r2}[(h_{3R'} - h_{2R'}) \quad (29)$$

$$CC_{Iso} = [T_{tank}(s_{5A} - s_{4A})] + m_{r1}[T_{tank}(s_{4R} - s_{3R})] + m_{r2}[T_{tank}(s_{4R'} - s_{3R'}) \quad (34)$$

The above cycles provide cooling and power which makes the system neither heat engine nor heat pump, so assessing the system performance seems different than normal systems. The study defined two different factors to evaluate the system performance; The first one is *COP* by considering the whole system as heat pump, in this case, the output power converted to an equivalent cooling capacity (which is a cooling produced using this output power to run a conventional AC system that has a COP of 3.5). Then the system COP was calculated based on the total cooling capacity and the energy consumed to produce LAir or LN2 as in using Eq.35 (which is 1080 kWh/kg for LAir and 1350 kWh/kg for LN2 (Ameel, 2013)) as in Eq35.

$$COP = \left[\frac{Total\ cooling\ capacity}{1080}\right]_{LAir} \quad \text{or} \quad COP = \left[\frac{Total\ cooling\ capacity}{1350}\right]_{LN2} \quad (35)$$

The second factor is *Recovery Efficiency* (η_{RE}) where the whole system considered as heat engine. In this case, the output cooling capacities were converted to an equivalent power (which is the input power needs to run a conventional AC system that has a COP of 3.5 to provide the same cooling capacity). Then the system *Recovery Efficiency* was calculated based on the total output power and the energy consumed to produce LAir or LN2 as in using Eq. 54.

$$\eta_{RE} = \left[\frac{Total\ output\ power}{1080}\right]_{LAir} \quad \text{or} \quad \eta_{RE} = \left[\frac{Total\ output\ power}{1350}\right]_{LN2} \quad (36)$$

4- **Results and discussion**

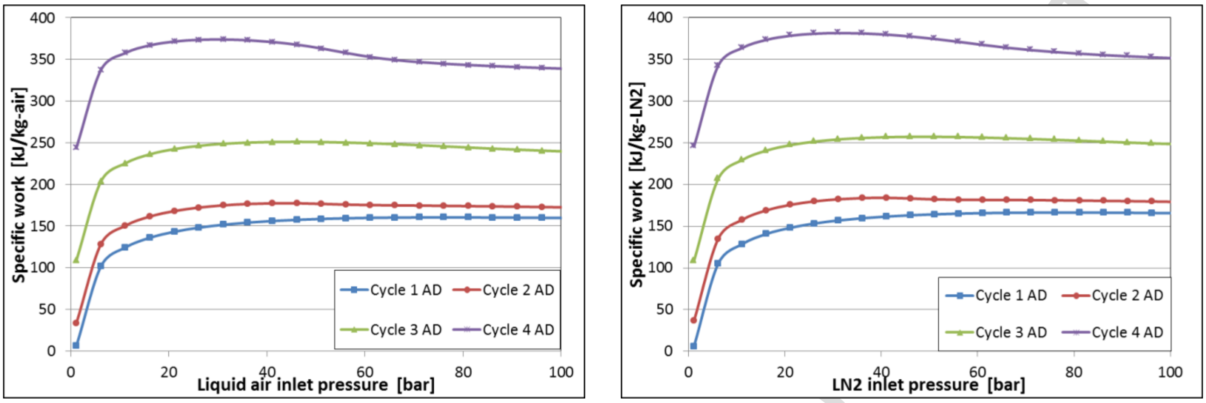
The proposed cycles use to provide cooling and power to commercial buildings at the peak times leading to save energy and to reduce the electricity peak demands with more environment friendly solution. The above cycles were investigated using two different clod storage mediums LAir and LN2, which are having almost similar physical and thermodynamic properties, and the different requirements to produce each of them. LAir consumes 20% less energy and less required components than that of LN2 needs and this will enhance the system performance significantly when LAir is used as the following results are showing;

Figs. 5-12 present specific output works, specific cooling capacities, the system COP and the system *Recovery Efficiency* for the adiabatic and the isothermal expansion processes for all proposed cycles either using LAir or LN2. For the adiabatic expansion scenario, the specific work vs the inlet pressure (P_{2A}) for all proposed cycles presents in Fig.5 (a, b) where Fig.5a relates to LAir and Fig.5b relates to LN2. The figure shows the specific output works have the same trend whether for the both working fluid (LAir or LN2) and there is no significant change after a value of inlet pressure of 30 bar. The maximum power output for the 2nd, 3rd and 4th cycles increases by 10.6%, 56.9% and 133.1% respectively compared with the first cycle when LAir is used and by 10.8% 54.8% and 129.5% consecutively when LN2 is used. The specific cooling capacities followed the same output power trend as shown in Fig.6 (a, b) and compared to the first cycle, the maximum values of the cooling capacities for 2nd, 3rd and 4th cycles show improvement by 3.0%, 15.2% and 36.8% when LAir is used and by 2.8%, 7.8% and 15.3% respectively when LN2 is used.

Regarding the isothermal expansion scenario, the specific output works and specific cooling capacities are higher than that of adiabatic one as Fig.7 (a, b) and Fig.8 (a, b) shown. This expansion process allows the system to increase the inlet pressure up to 500 bar or even more but after 300 bar there is no significant change indicating no reason to increase the inlet pressure further. Compared with the adiabatic expansion, the output works are increased by 3.1, 3.2, 2.6 and 2.0 times for the 1st, 2nd, 3rd and 4th cycles consecutively, when the system uses LAir and almost the same values when LN2 is used. Also, compared with 1st cycle the specific output works increased by 16.2%, 31.5%, 47.7% and for 2nd, 3rd and 4th respectively when LAir is used and by 13.7%, 32.5% and 48.4%, consecutively, when LN2 is used. The specific cooling capacities have almost the same output work trend as shown in Fig.8 and their maximum values are 1.5, 1.5, 1.4 and 1.3 times that of the adiabatic expansion for 1st, 2nd, 3rd and 4th cycles, consecutively,. Compared to the first cycle, the maximum cooling capacities of the 2nd, 3rd and 4th cycles show improvement by 2.8%, 7.8% and 15% when, respectively, LAir is used and 0%, 7.6% and 15%, consecutively, when LN2 is used.

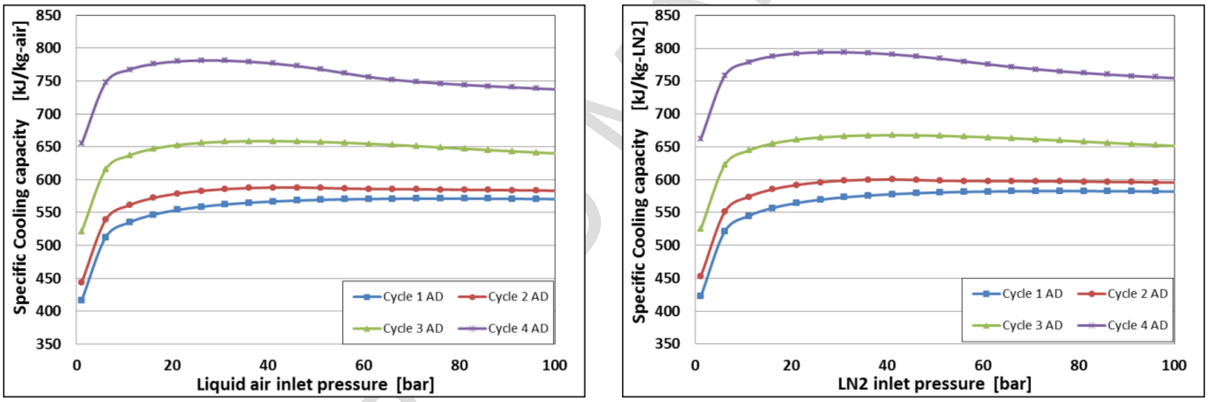
The systems performance were assessed based on its *Recovery Efficiency* and COP as mentioned in section 3, and for the adiabatic scenario, the *Recovery Efficiencies* and COPs of all proposed cycles are presented in Figs. (9, 10) and their trends look similar to that of the output works. The figures indicate that the 4th cycle has highest *Recovery Efficiency* and COP, and they reach 55% and 2, respectively, when LAir is used and 45% and 1.6, consecutively, when LN2 is used. However, for the isothermal expansion scenario, the *Recovery Efficiencies* and COPs of all proposed cycles are followed the output powers as shown in Figs. (11, 12). The figures show that, the *Recovery Efficiency* and COP of the lowest system performance (1st cycle) reach 70% and 2.4, respectively, when LAir is used and 55% and 1.9, respectively, when LN2 is used. However, in 4th cycle these values reach 94% and 3.3, consecutively, when LAir is used and 78% and 2.7, consecutively, when LN2 is used.

The figures show clearly that, the systems *Recovery Efficiencies* and COPs when LAir is used are more than 20% higher than that of when LN2 is used. The fourth shows the highest system performance while the 1st cycle shows the lowest.



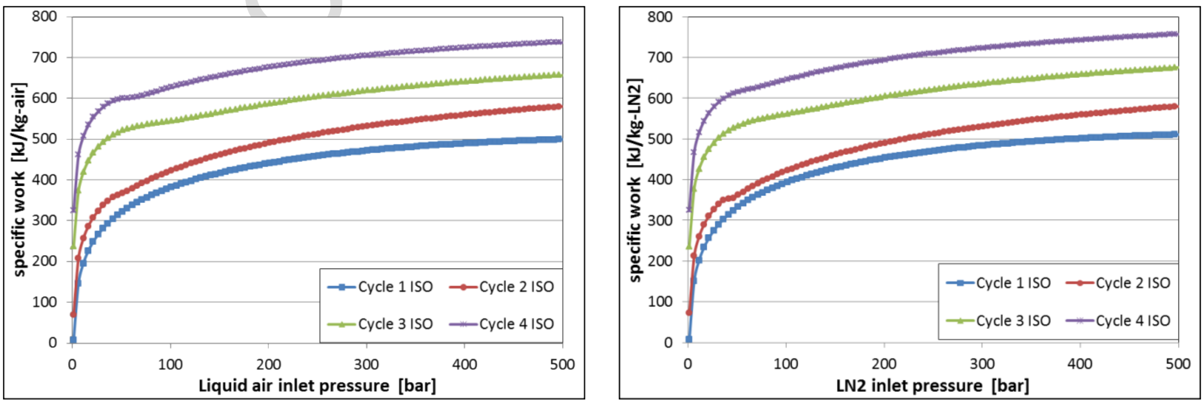
(a) (b)

Fig.5 specific output work at various inlet pressure for the adiabatic expansion



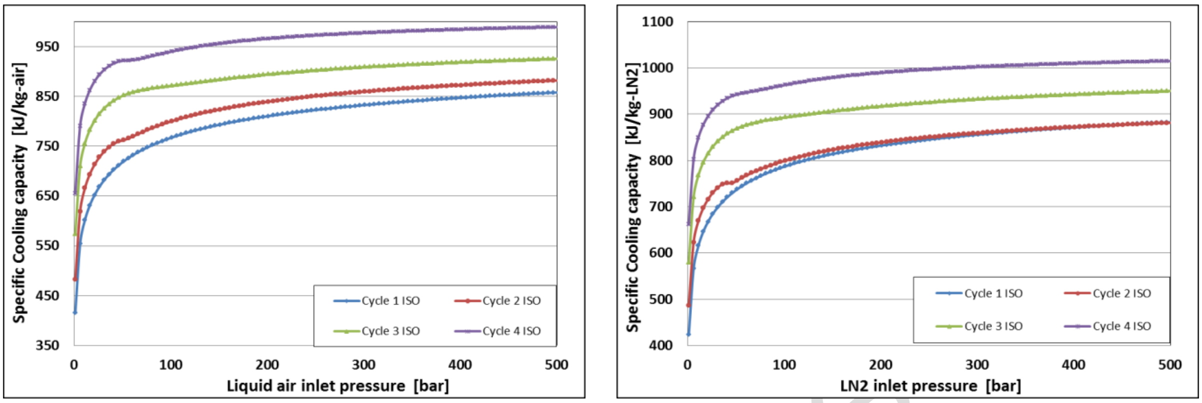
(a) (b)

Fig.6 Specific cooling capacity at various inlet pressure for the adiabatic expansion



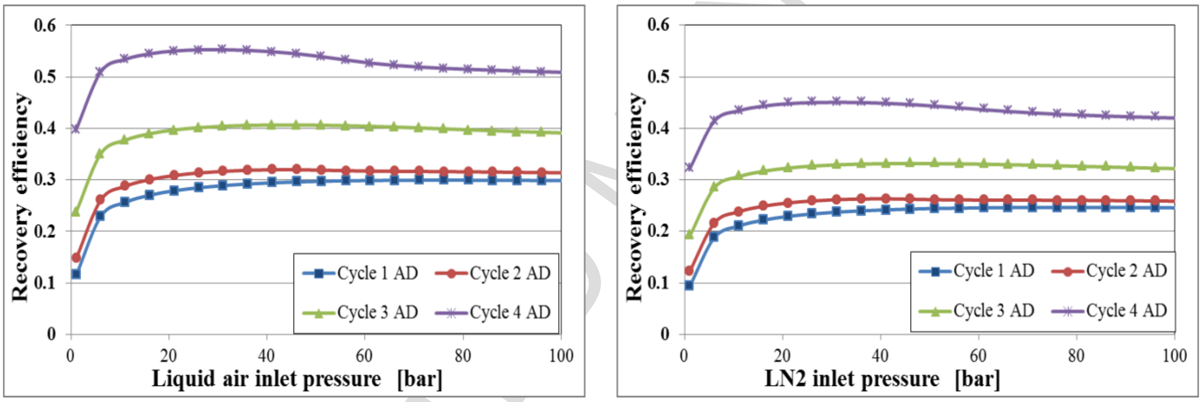
(a) (b)

Fig.7 specific output work at various inlet pressure for the isothermal expansion



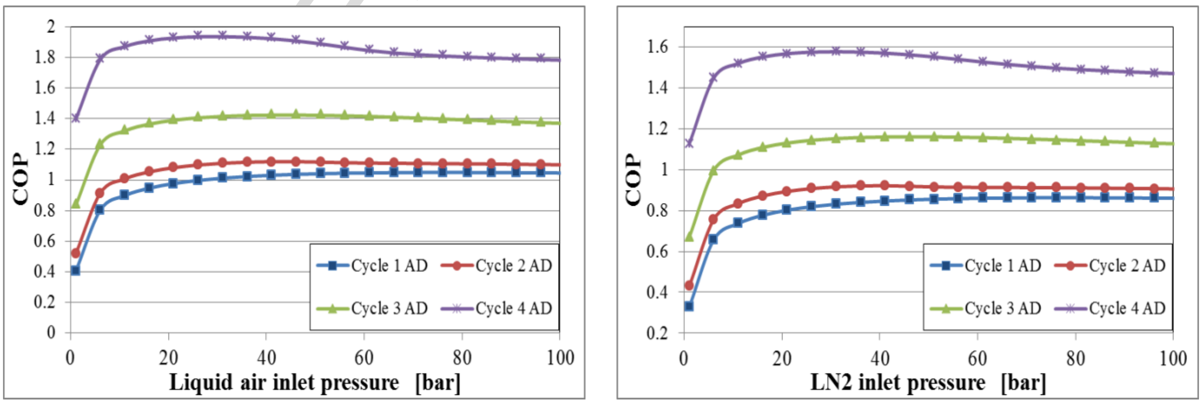
(a) (b)

Fig.8 Specific cooling capacity at various inlet pressure for the adiabatic expansion



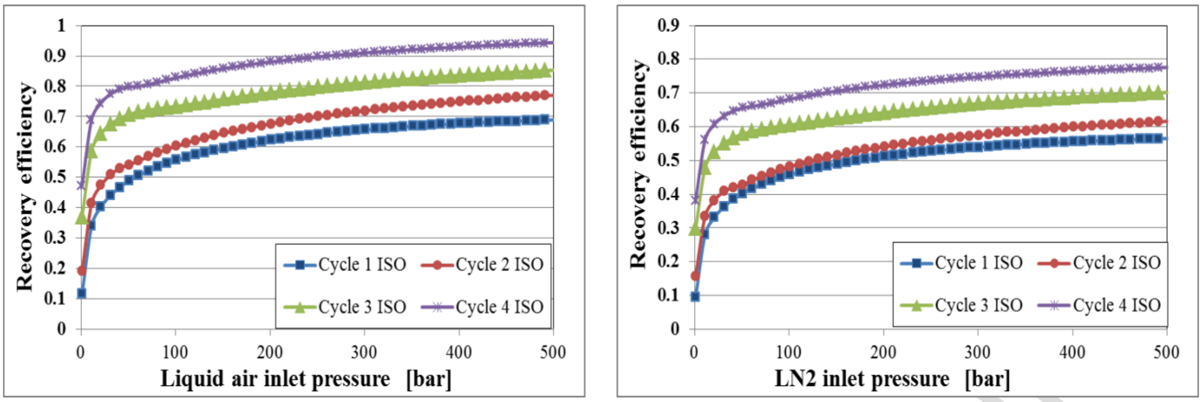
(a) (b)

Fig.9 *Recovery Efficiency* at various inlet pressure for the adiabatic expansion



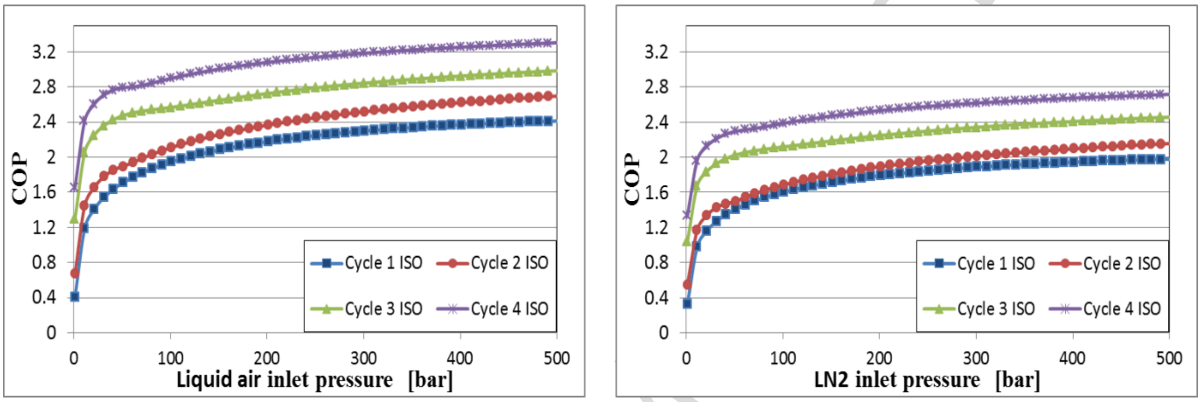
(a) (b)

Fig.10 COP at various inlet pressure for the adiabatic expansion



(a) (b)

Fig.11 *Recovery Efficiency* at various inlet pressure for the isothermal expansion



(a) (b)

Fig.12 COP at various inlet pressure for the adiabatic expansion

Table 1 presents a comparison between LAir and LN2 when they use to fuel the proposed systems in terms of output work, cooling capacity, *Recovery Efficiency* and COP. The table shows in all cycles the output works and the cooling capacities are slightly higher when LN2 is used with difference less than 4%, however, the *Recovery Efficiencies* and the COPs are higher by 21-25% when Lair is used indicating using LAir is more efficient than LN2.

Table 1 comparison between of the proposed systems in terms of maximum work output, cooling capacity, Recovery Efficiency and COP when they the two different fluids (LAir and LN2).

		Adiabatic Expansion				Isothermal Expansion			
Cycle No		1	2	3	4	1	2	3	4
Max. specific power output	Air	160	177	251	373	499	580	656	737
	Nitrogen	166	184	257	381	510	580	676	757
Difference [%]		3.6	3.8	2.3	2.1	2.2	0.0	3.0	2.6
Max. specific cooling	Air	571	588	658	781	858	882	925	989
	Nitrogen	582	600	667	793	883	881	950	1015
Difference [%]		1.9	2.0	1.3	1.5	2.8	-0.1	2.6	2.6
Max. recovery efficiency [%]	Air	29.96	31.98	40.66	55.29	68.95	77.09	85.33	94.43
	Nitrogen	24.66	26.34	33.18	45.07	56.53	61.64	70.19	77.61
Difference [%]		21.5	21.4	22.5	22.7	22.0	25.1	21.6	21.7
Max. system COP	Air	1.05	1.12	1.42	1.93	2.41	2.69	2.98	3.3
	Nitrogen	0.86	0.92	1.16	1.57	1.97	2.15	2.45	2.71
Difference [%]		22.1	21.7	22.4	22.9	22.3	25.1	21.6	21.8

A commercial building located in Ahwaz, Iran was selected as case study to find out how much energy the proposed systems can save compared with the conventional AC systems, and the building cooling load is shown in Fig.13. The comparison was made based on the cost of the required LAir or LN2 or the conventional AC system power consumption to meet the building cooling load. The results are very sensitive to the LAir and LN2 prices and at the current prices of LAir , LN2 and kWh electricity (Ahmad et ta., 2016) all above cycles in the isothermal expansion scenario consume less energy than the conventional system when LAir is used and only the 1st cycle consumes higher when LN2 is used as shown in Fig.14 (a, b). At this level of price the 1st, 2nd, 3rd and 4th cycles show savings up to 15%, 24%, 31% and 37.5%, respectively, when LAir is used, and -3.5%, 5%, 16% and 24%, consecutively, when LN2 is used. Where the negative sign indicates there is no saving achieved in this cycle.

It has been reported that the widespread of this technology and using the co-located systems leads to further reduction in LAir and LN2 prices leading to further energy savings and further reduction in CO_2 emissions (Akhurst et at., 2013). Fig.15 present the energy cost saving of each the above cycles at three different LAir and LN2 prices (3.5, 2.5 and 1.5 pence per kg). The negative values mean the conventional AC system has less cost of energy consumption, and all of these values except one refer to the adiabatic expansion process which is practically difficult due to the heat gaining from the surround where the temperature is much higher than inside the system. At the lowest LAir and LN2 prices the 1st, 2nd, 3rd and 4th cycles show savings up to 63%, 67%, 70% and 72%, respectively, when LAir is used, and 55%, 59%, 63% and 67% , consecutively, when LN2 is used. And at this level of price, the 4th cycle, which is the more complex one among the investigated cycles, shows savings only14%, 8% and 3% higher than the 1st, the 2nd and the 3rd cycles, respectively, indicating these is no point to use such complex system.

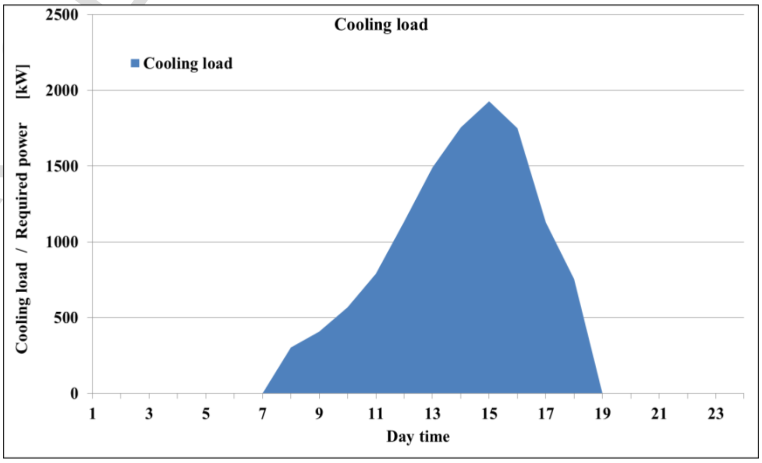
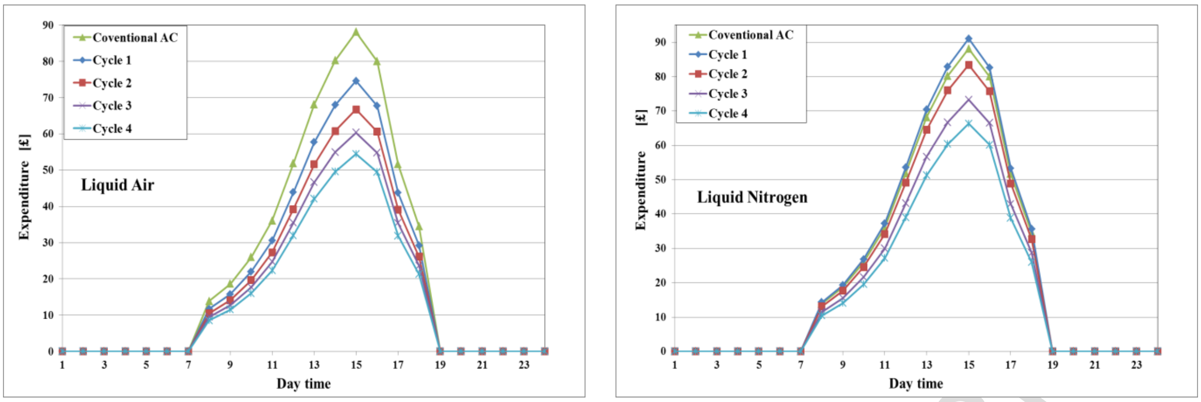
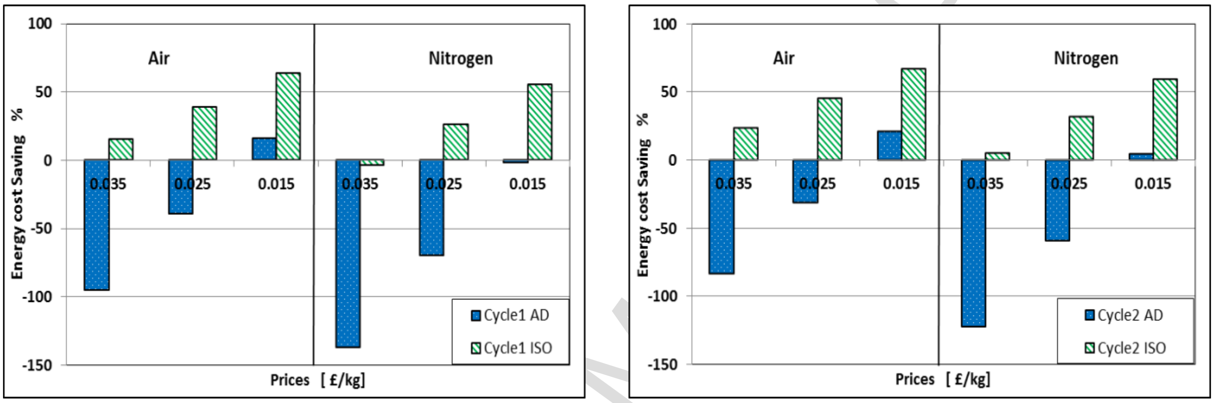


Fig.13. cooling load and the required power of the selected building (Navidbakhsh, et al., 2013)

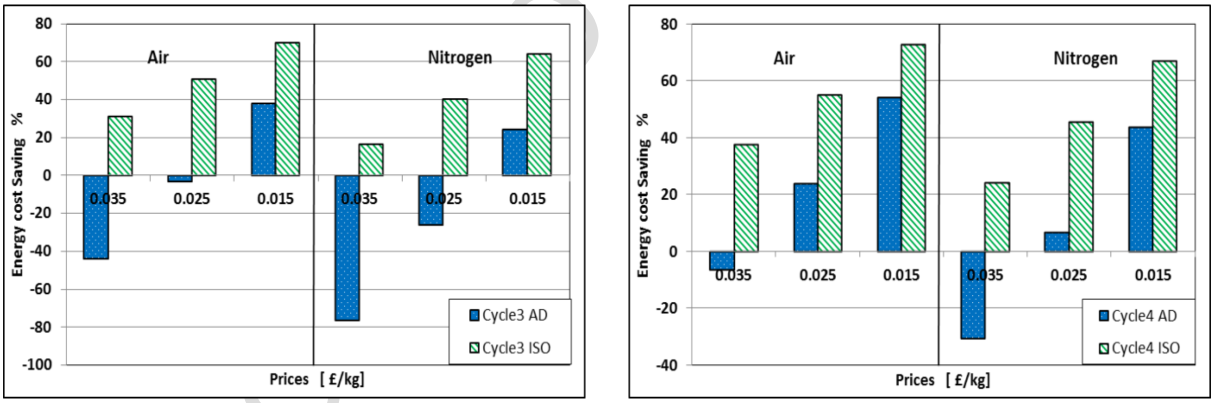


(a) Liquid Air (b) Liquid Nitrogen

Fig.14. Daily energy cost for the proposed cycles and conventional AC system



(a) Cycle 1 (b) Cycle 2



(c) Cycle 3 (d) Cycle 4

Fig.15. Saving of each proposed cycle against the conventional AC system

5- Conclusions

The conventional AC systems consume great amount of energy particularly during the peak times where the national electricity grid facing difficulties to meet the user's electricity demands. Consequently there is a need to modify the traditional AC systems or to produce new technology that leads to save energy, reduce the peak demands and reduce the CO_2 emissions. Cold energy storage in form of Liquid Air/N_2 is an attractive storage system and can be used to provide air conditioning and power. Four different cryogenic cycles use either LAir or LN2 to provide cooling and power to a commercial building were investigated and compared with the conventional AC system and results showed that:

1- The 4th cycle showed the highest system performance, and it recovered up to 94% of the energy stored in LAir and up to 78% of the energy stored in LN2, also it showed cost saving of the energy consumption up 73% when LAir is used and 67% when LN2 is used. However, the decisions about the selection of the most economical solution must take into consideration the complete design of the system including equipment sizing and investment costs.

2- LN2 system showed slightly higher (less than 4%) output works and the cooling capacities than LAir, however, LAir system showed 21-25% higher *Recovery Efficiency* and COP than LN2 due to its lower required energy to produce it.

3- Compared to the conventional system at the current LAir and LN2 prices the 1st, 2nd, 3rd and 4th cycles showed cost energy saving up to 15%, 24%, 31% and 37.5%, respectively, when LAir is used, and -3%, 5%, 16% and 24%, consecutively, when LN2 is used.

4- Extensive of using this technology leads to further reduction in the LAir and LN2 prices, and results showed that, at price level of 1.5 pence kg-LAir/LN2 the 1st, 2nd, 3rd and 4th cycles saved up to 63%, 67%, 70% and 72%, respectively when LAir is used, and 55%, 59%, 63% and 67%, consecutively when LN2 is used, leading to use the simplest cycle.

Nomenclature

h enthalpy kJ/kg
CC specific cooling capacity kW/kg-LAir
$\dot{m}$ mass flow rate kg/s
s entropy kJ/kg.K
W specific power kW/kg-LAir
m_r the closed Brayton or Rankin cycles mass flow rates to LAir mass flow rate
m_{r1} the first closed Rankin cycle mass flow rate to LAir mass flow rate
m_{r2} the second closed Rankin cycle mass flow rate to LAir mass flow rate

Subscripts

A Liquid air cycle
B Brayton cycle
Ad Adiabatic expansion
Iso Isothermal expansion
R Closed Rankin cycle/first closed Rankin cycle
R' Second closed Rankin cycle
$tank$ Cooling tank

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